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PROCESS SELECTION FOR NEW URANIUM ENRICHMENT PLANTS

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Presented to the
International Conference on Uranium Isotope Separation
in London, March 6, 1975

UNION CARBIDE

NUCLEAR DIVISION - GENERAL STAFF
OAK RIDGE, TENNESSEE

prepared for the **U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION**
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Over the years the group at Oak Ridge has given consideration to many uranium isotope separation processes. From the United States viewpoint, the leading established candidates for process selection for new plants are the gaseous diffusion and the gas centrifuge processes. The principal factors used in evaluating all processes are discussed and examples are given of the kind of evaluations made of ideas, proposals, or processes when relatively little information is available. The results of more detailed evaluations and comparisons of the diffusion and centrifuge processes are presented together with comparative costs and non-economic factors.

INTRODUCTION

Given the task of constructing an enrichment plant, the question of which process to select would seem to be a rather straightforward one based on technical and economic evaluations. The question, however, is complicated by special objectives and special situations in which different decision makers in different nations will find themselves. To cite some examples, the time available to develop technology, the resources available—technical and economic, and the competitive edge desired will require that the basic considerations which I will discuss be given different weights to suit particular situations.

In the United States, the special situation influencing the process selection question is the existence of the sizeable and eminently successful gaseous diffusion capacity. This dependable capacity is the basis for proceeding with confidence in having contracted to supply future U.S. and world needs of enriched uranium. Further, the existence of the diffusion capacity and technology has also meant that the selection of a process for <u>new</u> enrichment plants has not been of immediate urgency for

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us. We have had time to do research and development on new processes and could be fairly bold in seeking to improve diffusion technology and to develop new technologies as well. This paper reviews the techniques and approaches used in evaluating separation processes with particular emphasis on diffusion and centrifugation.

Background

Over the years, the United States has invested much effort in technology for uranium enrichment. Commercial-scale enrichment plants have been built using three processes. The electromagnetic process at Oak Ridge started operations in 1944, and Fig. 1 shows an array of 96 calutron units involved in enrichment from normal to 10-15 percent uranium-235. A second step, as shown in Fig. 2, was necessary to carry enrichment to 90-95 percent. A thermal diffusion plant was placed into operation in Oak Ridge in 1945, and Fig. 3 is a photograph showing that plant as the dark building in the foreground with the Oak Ridge diffusion plant in the distant background. A view of the thermal diffusion columns is shown in Fig. 4. This plant operated with uranium hexafluoride at 65 atm. pressure, requiring more than 200 times the work required by gaseous diffusion; and though it turned out product at 0.86 percent uranium-235, the process was abandoned when the diffusion plant proved successful. The gaseous diffusion process proved highly successful in initial operations, and the new diffusion plants built at Oak Ridge, Paducah, and Portsmouth, Ohio, in the 1950s (Fig. 5) were much more efficient and just as dependable. Research and development in the 1960s was also highly productive and is now providing the know-how to improve the efficiency and capacity still further in the current cascade improvement and uprating programs.

In addition to these "commercial" ventures, the United States has continually sponsored research and development on isotope separation. During the research and development efforts which led to the first commercial plants in 1944, all then known possibilities were studied, including two which are now the subject of renewed interest: the gas centrifuge and photochemical processes. Since those early days, many new ideas and modified old approaches have been considered. Contrary to the statements once common in older textbooks, many physical and chemical characteristics can be exploited to effect a slight separation of the isotopes. This fact, coupled with the creativity of scientists and engineers, has generated dozens of imaginative and novel proposals over the years. Our Oak Ridge group has studied hundreds of proposals from various sources over the past 20 years. Further, at Oak Ridge we have undertaken experimental programs to evaluate a number of methods proposed for uranium isotope separation including: chemical exchange, fractional distillation, photochemical separation (pre-laser), ion exchange, electromigration, aerodynamic processes, as well as gas centrifugation. The calutrons have been gradually perfected and applied to the separation of most of the stable and some of the radioactive isotopes.

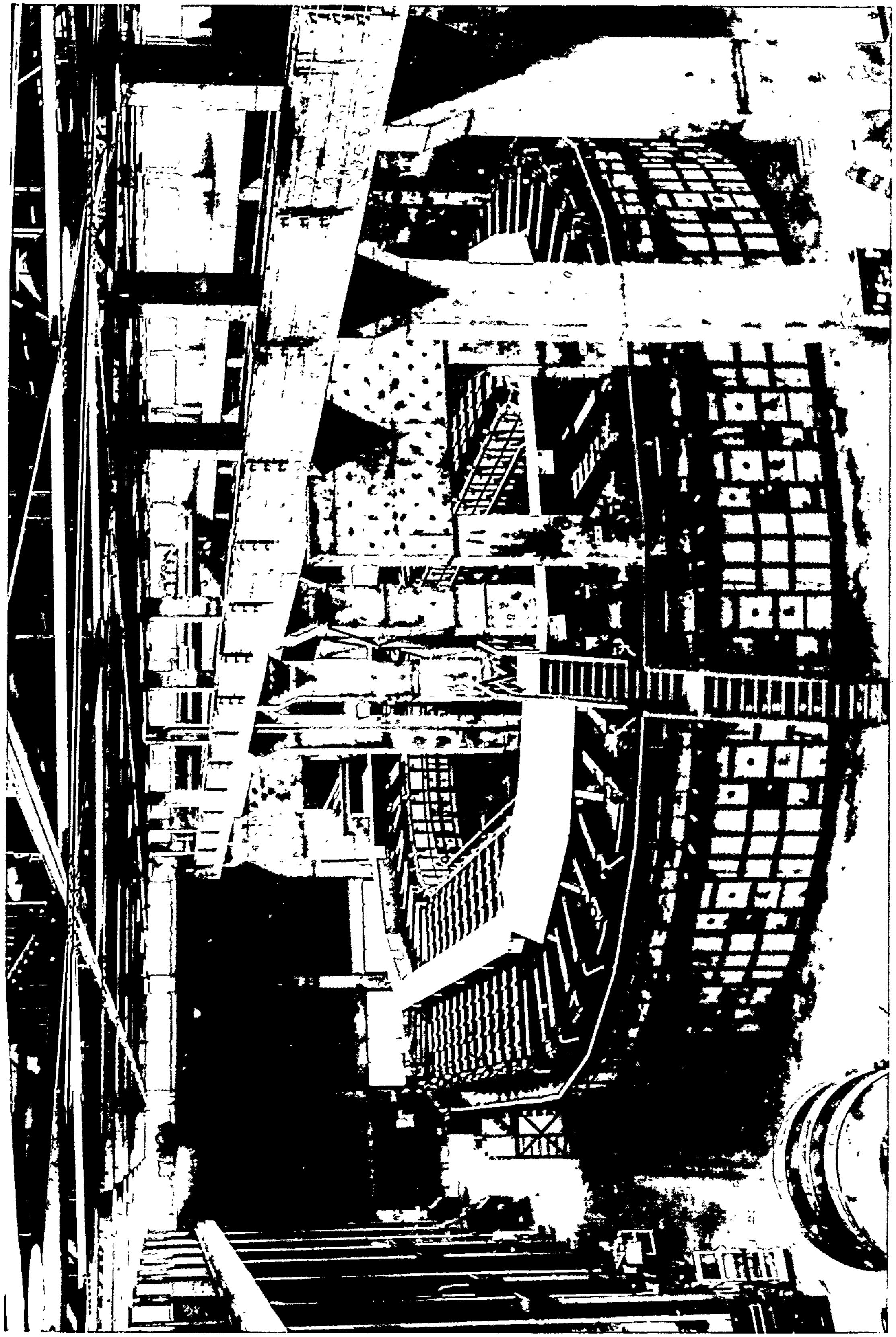

FIGURE 1
ELECTROMAGNETIC PROCESS - α UNITS AT Y-12

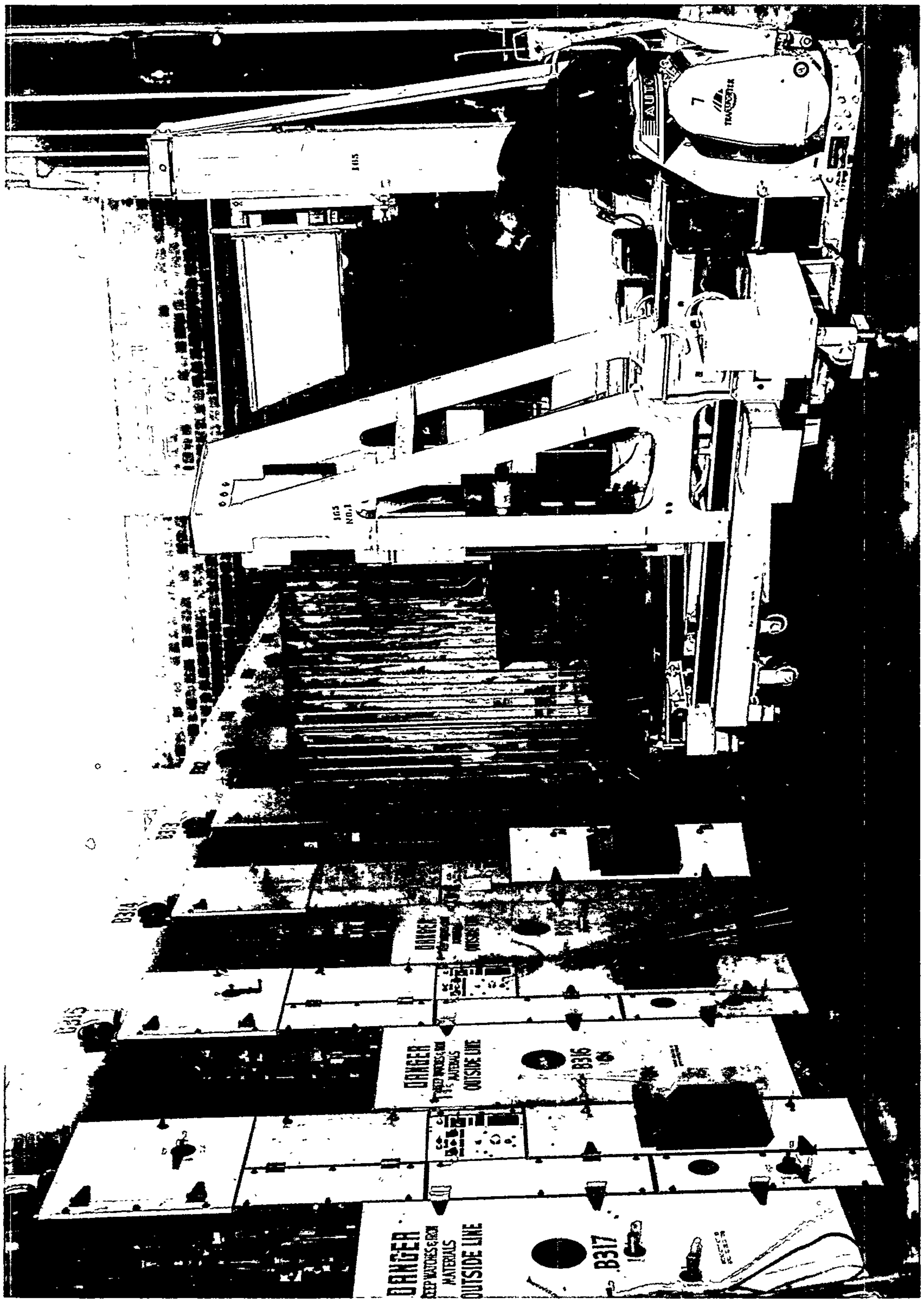

FIGURE 2

ELECTROMAGNETIC PROCESS - β UNITS AT Y-12

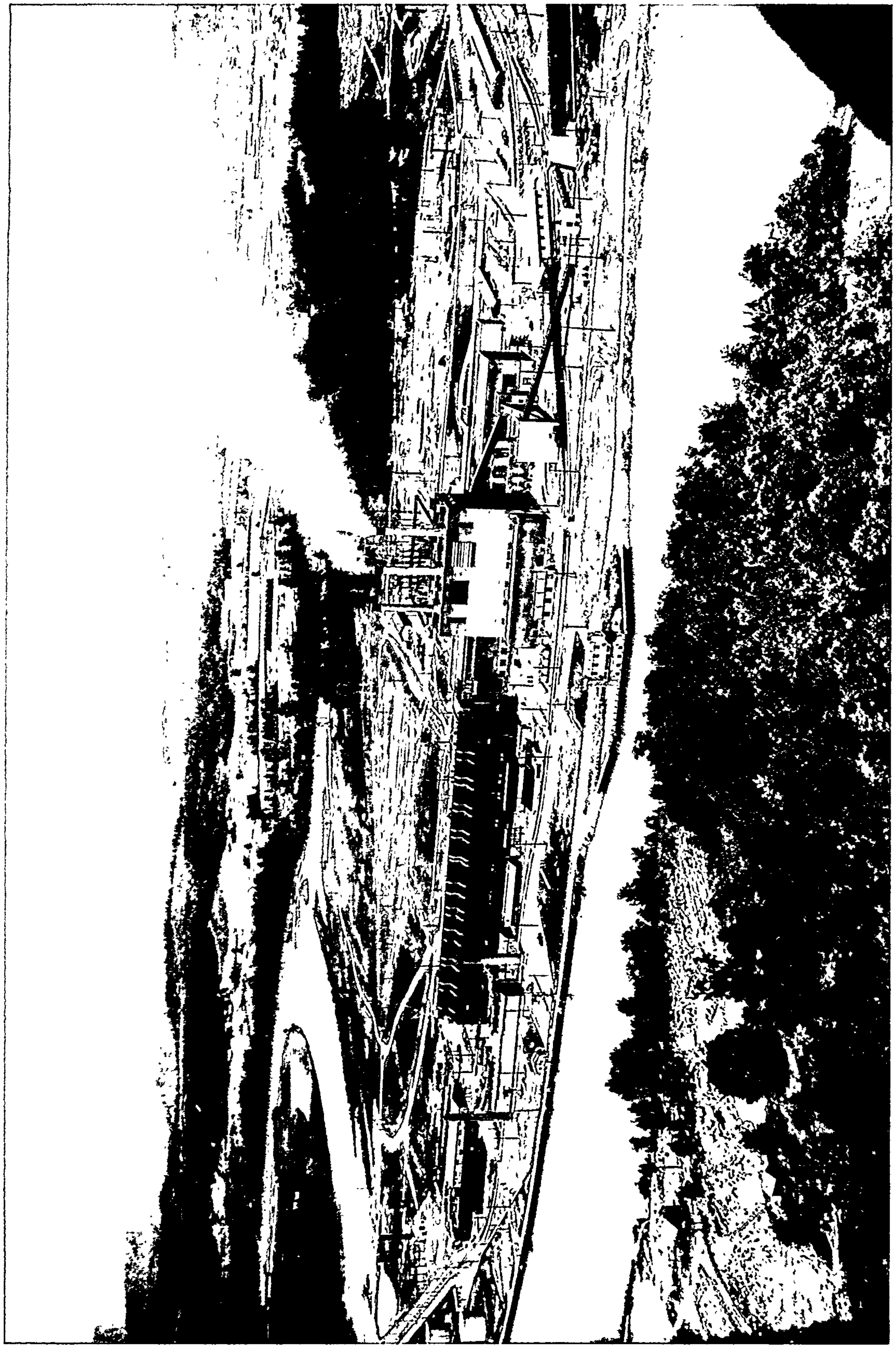

FIGURE 3
THERMAL DIFFUSION PROCESS - S-50 PLANT

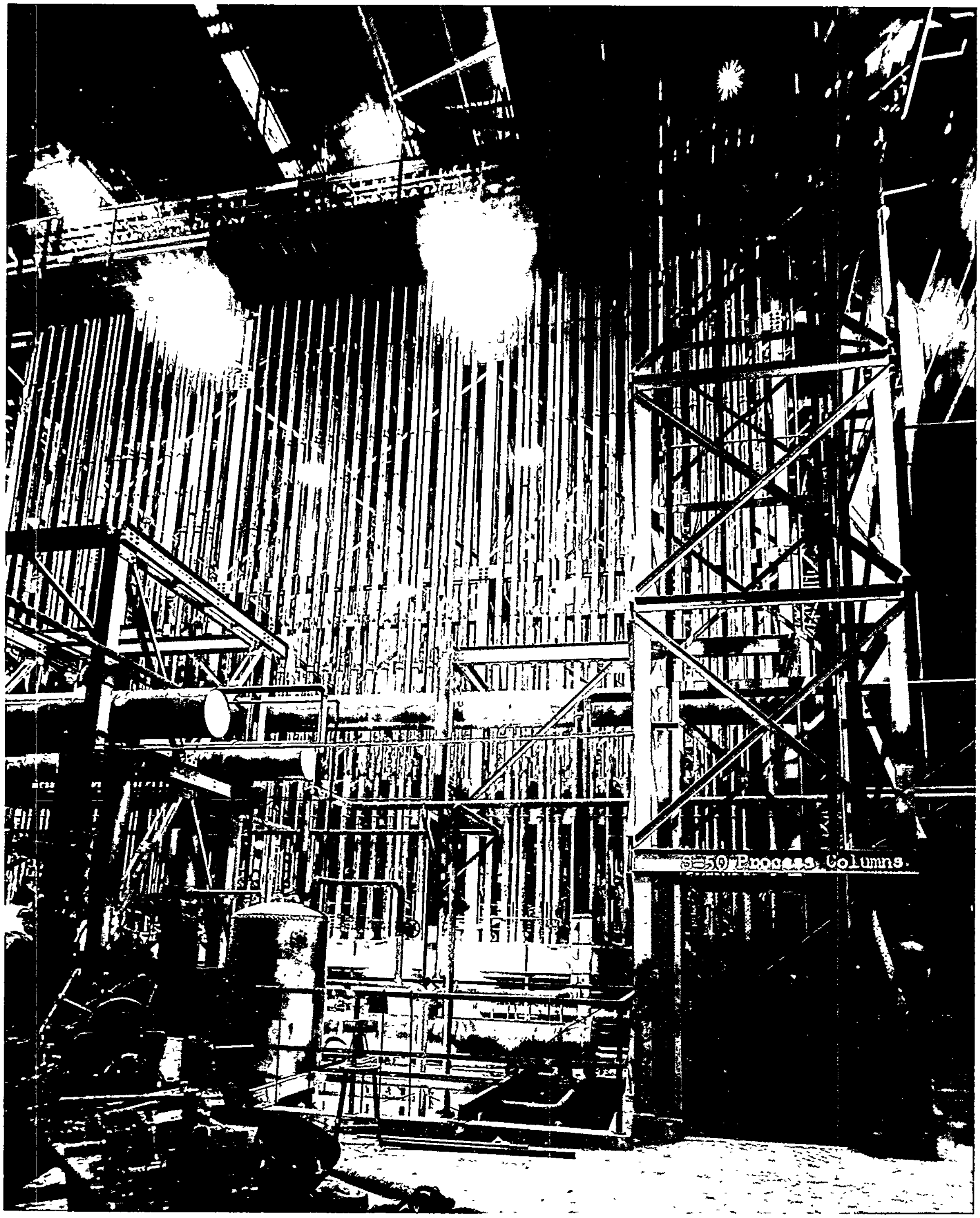

FIGURE 4

THERMAL DIFFUSION PROCESS - COLUMNS AT S-50

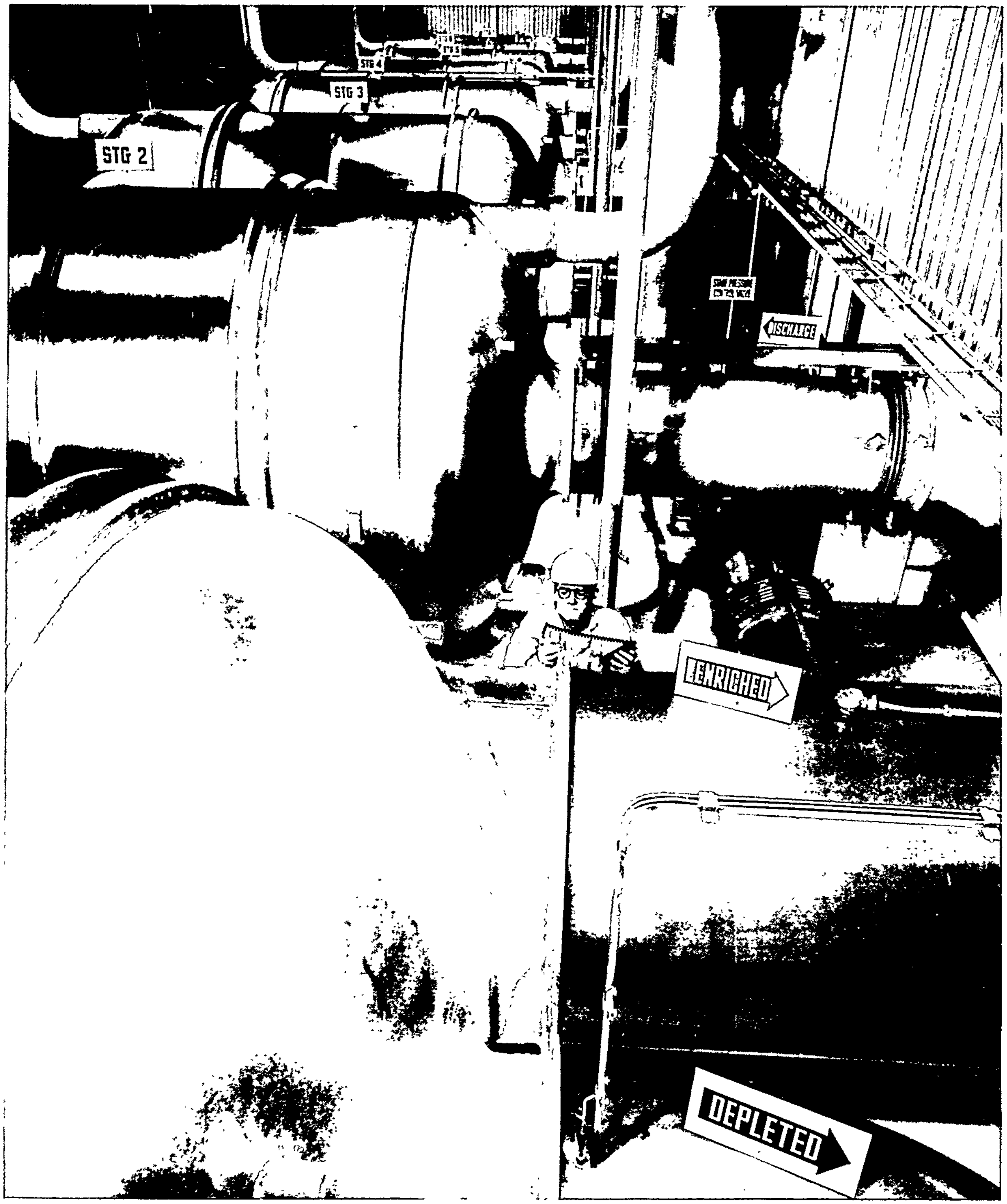

FIGURE 5

GASEOUS DIFFUSION PROCESS - K-33

Principal Factors for Evaluating Processes and Their Use

The principal factors are shown in Table 1; (a) separation factor per separation unit or stage, (b) throughput per unit, (c) in-process inventory, (d) capital cost, and (e) operating cost. Of course, what is wanted ideally is (a) a process which will remove all or a great portion of the uranium-235 contained in the uranium fed to a separating unit; (b) a process which has a high throughput capability—we will need tonnes of product, not grams; (c) a process with a low in-process inventory, of course to minimize investment, but also to minimize equilibrium time. At startup, the inventory must be enriched before any product is obtained. Further, during operations it is necessary for the plant to respond quickly to operating changes. Finally, (d) and (e), we want the process to have low costs both in (d) initial investment and (e) long-term operation.

TABLE 1

PRINCIPAL FACTORS IN EVALUATION OF PROPOSED PROCESSES

a. Separation factor per separating unit or stage
b. Throughput per unit or stage
c. In-process inventory or process material hold-up
d. Capital cost
e. Operating cost
f. Unit cost of separative work, \$/SWU

Operating costs will reflect the power intensiveness of irreversible processes; but in these energy-sensitive times, there is some merit in considering this as a separate *desideratum*, and some experts do. For example, Vanstrum lists as one of the characteristics of an "ideal" separation process that it be a thermodynamically reversible process with minimum energy requirements (ref. 1). In a similar vein, dependability or reliability of the plant is so vital in assuring supply of product to customers that sometimes, for emphasis, it is treated as a factor separate and apart from conventionally defined operating costs.

Several other factors need to be considered, but are more difficult to assess. One is time and the cost of developing the technology, i.e., both the work on the laboratory scale and the translation of that research and development to the commercial scale. Another factor is the potential for improvement of the originally installed technology and performance of the plant.

When enough is known about the performance of candidate processes to permit study of actual operating costs or to develop engineering cost estimates, the evaluation work is focused on these cost estimates. The cost estimates for new enriching capacity can be converted into unit costs of separative work, and ultimately prices, if assumptions are made with respect to factors such as capital recovery rates, assumed plant load factors, expected future power costs, desired product inventory levels, structure and financing of the enrichment enterprise, as well as a number of other items representing individual business judgements. These factors will differ among prospective uranium enriching enterprises. Nevertheless, it has been useful to compute unit costs, determined by conversion of the capital investment to an annual charge on a generally consistent basis to combine with annual operating costs, as one way of comparing the technologies of different separation processes. If valid and consistent assumptions are used, the unit cost of separative work is the best single figure of merit for process evaluation and comparison.

We, of course, want the unit cost to be as low as possible. If we know enough about the process to have included a fair estimate of all costs, it should be a good measure of the process value. It should reflect costs of environmental or employee protection where necessary, as well as reflecting the process thermodynamics and equipment life. Low unit cost of separative work will encourage good utilization of the uranium-235 in the feed supply. In the United States, our enrichment technology improvement programs are justified and directed toward obtaining separative work at the lowest unit costs. We require that research proposals show a potential for reduction in costs of separative work if the work is to be carried beyond small scale research and development, since very substantial expenditures of funds and other resources are required to develop new processes and advance their technology to the point at which sound engineering cost estimates are possible.

Examples of Results of Preliminary Evaluations

Over the years, hundreds of research proposals and suggestions for isotope separation processes have been forwarded to our Operations Analysis and Planning group at Oak Ridge for evaluation. Most often the proposals that come in are based on computations or on a modest amount of experimental work. Where data are available, they are usually limited to measures of a separation factor (seldom with uranium) or to estimates of energy requirements. Evaluations carried out on such proposals customarily take the form of making the most of what appear to be unique attributes, making comparisons with gaseous diffusion or centrifugation. Frequently, one can rule out the candidate. Less often one cannot do so, and recommends further work or study. Many of the preliminary studies done by the Oak Ridge group over the past 20 years were incorporated in the excellent survey of the field done by Benedict et al. two years ago (ref. 2). That survey covered 25 types of processes, and a great many versions of those have appeared and been evaluated from time to time.

High Separation Factor Methods. Many proposals seem to originate in the interest of obtaining a large separation per stage or unit. Perhaps the electromagnetic process is the classic example. The process works reliably and very large factors can indeed be obtained. But limited throughput is a severe penalty leading to high capital costs. It was found that when the ion beam current was increased in order to increase throughput, the quality of the separation was markedly reduced and beam scattering occurred. The batch nature of the chemical processing required to collect product and recycle material led to high operating costs, which together with the high capital costs far outweigh the economic attractiveness of the high separation factor. Gaseous diffusion proved much more economical, despite a separation factor (α - 1) more than three orders of magnitude smaller!

The laser process is a proposal of more current interest which is hoped to offer a very large separation factor. Although the principles of photoexcitation separation processes have been known for years, until the development of the laser no encouragement could be provided for the schemes studied and proposed. In principle, a single laser "stage" may effect a large separation. Throughput per unit of capital expended may be high compared to the electromagnetic process. The difficulties which may be encountered in collection, cascading, or scaling up, etc. remain to be seen. Capital and operating cost estimates are major unknowns. Any comparison with developed processes depends for its validity on the validity of the assumptions chosen for the efficiencies and potentials of the various laser process elements. The possibilities of attractive economics for laser separation cannot be ruled out. Experimental work is under way in several countries including the United States, where work is being sponsored by the Government as well as by private firms.

Aerodynamic Processes. For about the last 15 years, Dr. E. W. Becker and his associates in Germany have been developing the Becker nozzle, an aerodynamic process. Like gaseous diffusion, it is an irreversible process; and its energy requirements are high and comparable to diffusion. In separation per stage, however, it surpasses gaseous diffusion.

A variety of other aerodynamic processes is being proposed both in the U.S. and elsewhere. In this field—in which the theory is not completely understood—one cannot rule out the possibility of some unforeseen invention which could significantly advance technology and might, therefore, make aerodynamic processes competitive.

Low-Power Approaches. Because of the large power requirements for thermodynamically irreversible processes like gaseous diffusion, many reversible processes such as gas chromatography, distillation, chemical exchange, and ion-exchange crop up from time to time in the form of separation process proposals. For heavy elements such as uranium, the separation factors, which depend on different vapor pressures or zero-point energy differences between the isotopic species, have been found experimentally to be very small, even compared to diffusion. Compensation for a low separation factor must be accomplished by using tens of thousands of stages and very large throughputs. This leads to large process equipment volumes and, in the case of distillation, for instance, to the use of expensive high-efficiency packing materials in the columns. Capital costs soon become excessive. Furthermore, in liquid systems the inventory of process material is large. Two noteworthy penalties are associated with large process material inventory. We have examined distillation processes, for example, in which we found that the annual interest charge alone on the investment in uranium inventory equals the entire annual cost of separative work from the gaseous diffusion plants. Additionally, in such liquid-phase processes the net enriched inventory in the plant is so large and the net upward transport of desired component is so small that the equilibrium time, which is the time required for the plant to enrich its internal inventory and establish its steady-state gradient, must be measured in years. In the evaluation of fused-salt electromigration plants, we have calculated equilibrium times measurable in terms of decades. Needless to say, such long equilibrium times eliminate most liquid-phase processes from consideration. To overcome the large inventory and equilibrium times of liquid-phase processes, gas exchange chromatography has frequently been proposed. Thus far, separation factors determined have been too small to be useful.

In this hurried summary of the results of preliminary evaluations on some proposals for enrichment processes, we have mentioned only a very few. The purpose in mentioning them is not to highlight the most promising methods nor the least, but to illustrate the point that there is a complex of criteria to be considered in evaluations. Certainly, it is constructive if it can be shown that a proposal can be ruled out on the basis of one factor alone. But to merit further consideration, a process must, so to speak, get good enough grades (or fail to be ruled out) in each of the areas of the examination when competing with established processes. These preliminary evaluations require relatively little of our time, and our major evaluation efforts are focused on the comparison of the gaseous diffusion and gas centrifuge processes. I would now like to turn to a description of this evaluation work.

<u>Diffusion and Centrifuge Comparisons</u>

Much work was done on the gas centrifuge in the early 1940s before choosing diffusion as the process for the early production plant. Late in the 1950s, the USAEC evaluation of the potential of the gas centrifuge led to the decision to considerably expand the experimental program. Progress to date has been good. During the same past 15 years, improvement of diffusion technology has continued, and an improving, "moving target" standard for comparison has been the result. Some of the considerations in evaluating these two process candidates are presented.

<u>Separation Factor</u>. In diffusion, the separation factor is low, leading to the requirement for many hundreds of stages in series to produce reactor fuel grade enrichment levels of two to four percent. The theoretical limit on the separation factor is well defined. Centrifuges are not so limited. By making the centrifuge spin faster and by making the rotor longer, one can in principle continue to increase separation per machine. Mechanical complications and strength of materials pose practical limits, but only a few centrifuges in series are needed to produce reactor grade enrichment levels.

Throughput. On the other hand, diffusion is much to be preferred over the centrifuge in this area. Large areas of barrier material may be designed into one stage, and gas compressors could be increased in size well beyond those we now use if more throughput were desired. Current stage compressors have motors as large as 1600 kilowatts, and much larger ones will be used in the improved cascades. The throughput of the centrifuge is limited, and so a large number of centrifuges must be connected in parallel to provide needed flows if plant capacities comparable to the diffusion plants are to be provided.

In-Process Inventory. Both gaseous diffusion and gas centrifugation are obviously gas-phase processes as their names indicate. Despite the low separation factor, a diffusion plant can enrich its own inventory in a few weeks to reactor fuel grade levels. Such times are quite acceptable, as is the response of the process to normal changes in operating conditions. The inventory requirements for centrifugation are lower, and response times are shorter. The magnitude of the differences are not very important for process selection.

Capital Costs. In the case of the diffusion and centrifuge processes, sufficient information is available to warrant generation of detailed cost estimates. Such cost estimates are the subject of continuing study and modification. An example of the results of one such study has been previously published and is presented again in Table 2 for illustrative purposes (ref. 3). These estimates were prepared for process comparison purposes and should not be viewed as current engineering estimates of the cost of construction of separation plants. In the case of gaseous diffusion plants, two types of technology are shown. "CIP technology" refers to that technology (barrier quality, compressor performance) which will be in hand at the completion of the present diffusion plants improvement program late in the 1970s. "Advanced technology" refers to new equipment geometries and stage arrangements, which take advantage of the design freedom available when a new plant is built—in contrast to working with existing building and equipment layouts. Stages of advanced design have not yet been built or tested, but their design is not so different that any fundamental problem is expected. Centrifuge plant costs are given as a range which reflects both alternative technologies and expected economies which may result if second and third plants are built. Accordingly, it could be expected that the first centrifuge plant built may be near the top of the range in cost. Diffusion plant costs can be estimated more accurately than can centrifuge plant costs, because of experience.

Some comments on these capital costs may be of interest:

a. One notes that the range of specific investment required for gas centrifugation envelopes the estimates for gaseous diffusion, the lower estimate being as low as diffusion and the highest being considerably higher. It is interesting to recall statements made in some early conversations about the gas centrifuge process in the 1960s. Some people compared it to the simple cream-separator and visualized that this process would make possible enrichment plants

TABLE 2

ENRICHMENT PLANT COMPARATIVE CAPITAL COST ESTIMATES
(8.75 million SWU/yr plants at new site,
FY 1974 dollars, ref. 3)

	Capital Cost	Specific Investment
Gaseous Diffusion		
CIP Technology	$1.40 billion	$160 SWU/yr
Advanced Technology	$1.20 billion	$137/SWU/yr
Gas Centrifuge Range		
Early Plants	$1.71 billion	$195/SWU/yr
Later Plants	$1.13 billion	$129/SWU/yr

having substantial product rates hidden in a garage (usually in someone else's country). Although it is true that only a few centrifuges are needed to produce substantially enriched uranium, large numbers of centrifuges are needed to obtain substantial outputs.

b. Garages have more recently been mentioned again by some of our enthusiasts, this time for the laser process; and, of course, we would hope that this process might be the exception to what seems to be the trend thus far that the cost of other essentials is high relative to the cost of the separating element itself. In the centrifuge plant estimate, the cost of the centrifuges was 32 percent of the capital cost. The auxiliaries accounted for 68 percent of the capital investment. In the diffusion plant estimate, the cost of all the major components was 39 percent of the cost, auxiliaries accounting for 61 percent.

c. With regard to the treatment of the capital cost of the power plants, it is our practice here and in most of our other evaluation studies to assume that power will be purchased from others. Power costs, therefore, are reflected as part of the operating cost of the process and not included as part of the specific investment.

d. Capital costs for diffusion plants "at new sites" are for plants which can perform the entire task of enriching normal uranium to two to four percent uranium-235. Such plants utilize three different sizes of diffusion plant equipment, such as diffusers, compressors, and valves. Informally, we refer to such independently operable plants as "stand-alone" plants. One can expand an existing capacity by adding equipment of only one size at considerably less capital cost than that required for construction of independent plants. We refer to these as "add-on" plants. Large-capacity additions can be made to the existing plants in this fashion.

Operating Cost. Operating cost estimates for the processes are summarized in Table 3. The impact of the higher power requirements of diffusion is seen. The lower energy requirement for the centrifuge process may ease lead time requirements for power acquisition, allow more flexibility in siting a plant, and reduce the environmental impact associated with waste heat disposal. Because the operating cost for diffusion is primarily power cost and for centrifuge is primarily labor and materials, choosing different escalation factors (when predicting future costs) for power than for labor and materials can easily "tip the balance" and must therefore be undertaken with appropriate caution.

Reliability of the equipment and cost of replacements impacts operating costs. Diffusion plant equipment has proved to be highly reliable. This subject is treated in detail in the paper by Hopkins at this conference (ref. 4). With the centrifuge process an economic trade-off between performance and life is made, and in the U.S. centrifuge program this optimization is carried out using the unit cost of separative work as the criterion. Our studies have shown that once a reasonable lifetime is

TABLE 3

ENRICHMENT PLANT OPERATING COST ESTIMATES
(8.75 million SWU/yr plants at new sites
in FY 1974 dollars, ref. 3)

	Operating Cost Excluding Power $ million/yr	Power Cost* $ million/yr	Operating Cost Including Power* $ million/yr
Gaseous Diffusion			
CIP Technology	16 ($1.83/SWU)	210	226 ($25.8/SWU)
Advanced Technology	16 ($1.83/SWU)	210	226 ($25.8/SWU)
Gas Centrifuge			
Early Plants	115 ($13.14/SWU)	21	136 ($15.5/SWU)
Later Plants	70 ($8.00/SWU)	21	91 ($10.4/SWU)

* Power cost at 10 mills/kWhr.

achieved, there is a diminishing benefit of further reductions in machine repair and replacement cost.

Unit Cost of Separative Work. Fig. 6 presents unit cost of separative work derived from the capital and operating costs presented and gives a feel for the range of uncertainties imposed by different power costs in the case of diffusion and for different technology assumptions in the case of the centrifuge. The more advanced centrifuges under development have unit costs at the lower part of the range of estimates shown (ref. 5).

With ten-mill power and an annual capital charge rate of 16 percent per year, these studies indicate about 50 percent of the cost of separative work from diffusion plants is due to capital recovery and about 46 percent of the cost is due to energy. The balance of four percent is due to other operating costs. In the case of the centrifuge process, the capital recovery component is nearly the same because of the almost balancing advantages of high unit separation factor for centrifuges and high unit throughput advantages for the diffusion process. Our present opinion is that centrifuge plants will be somewhat more capital intensive than diffusion plants. We would expect our first large centrifuge plant to cost more than a comparable diffusion plant and certainly more than successive centrifuge plants.

Other Factors. In addition to the cost comparisons of the kind we have been discussing, there are other factors or implications which also require consideration in process selection. Some of the more interesting of these are shown in Table 4. Four basic areas are cited: process maturity (which is of interest in reducing both technological and business risks); plant size considerations (which not only set the initial stake required to get into the game but also affect the usability of the plant as it is put on-stream and the later potential for capacity expansion); power requirement of the plant (which has siting implications); and finally, the existence of a supporting industrial base (which speaks to the dependability of plant construction schedule estimates, the coordination problems to be faced by a potential enrichment plant builder, and to the technological and business risks involved).

Process Selection Status and Perspective

It will be apparent upon review of the comparisons of the diffusion and centrifuge processes, using the evaluation approach outlined, that the choice between these candidates must be based on trade-offs. Neither process is superior in all areas of evaluation. As further information is developed, evaluations will be sharpened and better choices can be made.

In the case of the diffusion process, actual construction of large production plants and 30 years of highly dependable large-scale operation together with a concurrent highly productive research and development effort costing $225 million give the best type of assurance that new plants can be built and operated as designed. Although the technology

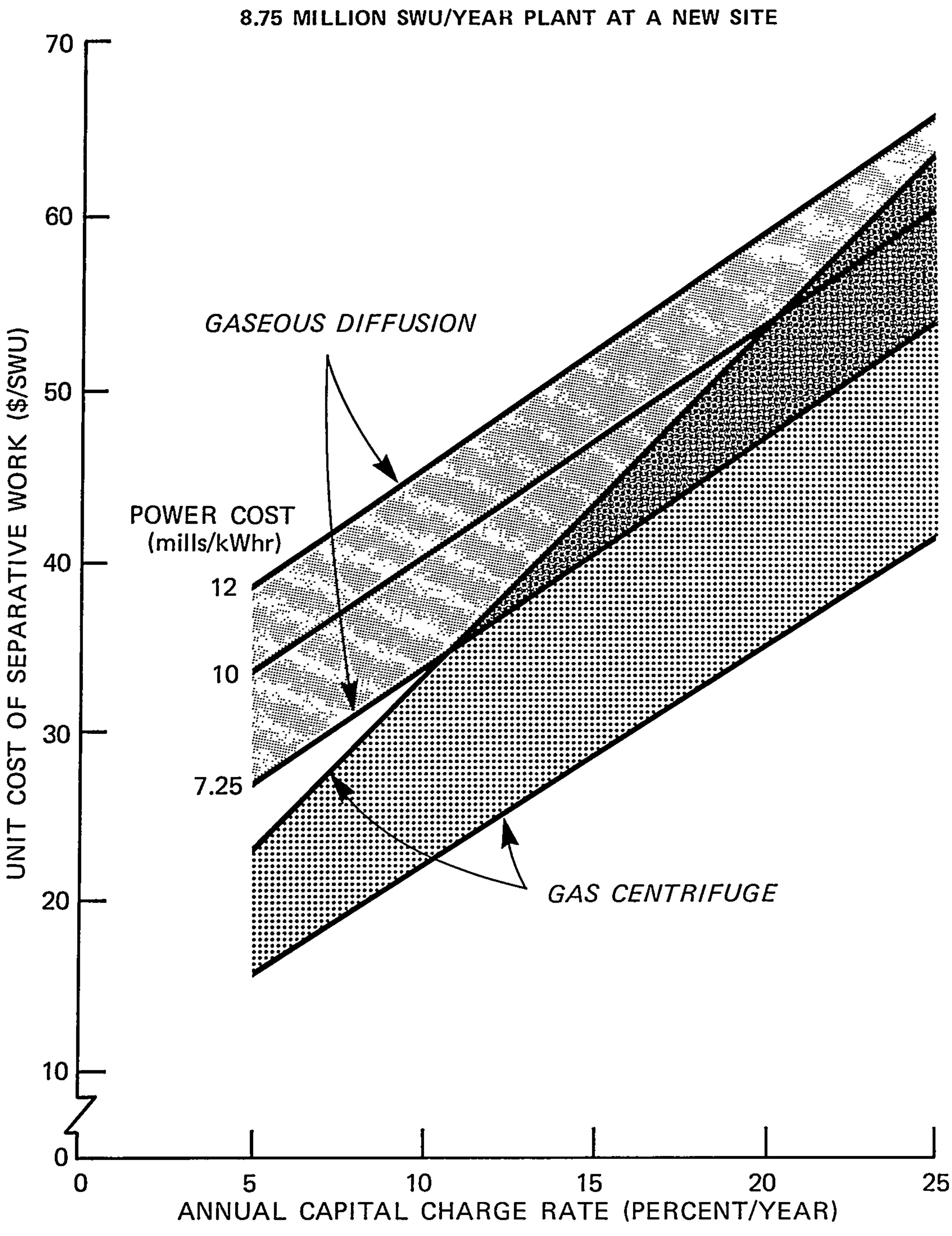

FIGURE 6

UNIT COST COMPARISONS

TABLE 4

OTHER FACTORS AND CONSIDERATIONS

	Gaseous Diffusion	Gas Centrifuge
Maturity	+ 30 years of industrial experience—three large plants	· 14 years of intensive development
	+ minimum technological risk: R & D over $225 million	+ less exploitation of technological potential
	+ capital and non-power operating costs are predictable with considerable accuracy	— costs based on first-cut designs are more subject to change
	+ minimum business risk	— Mass production/operation not yet demonstrated
Plant Size	— large for economy; takes hundreds of units in service to produce product	+ can be built up in modules
	— need most of plant to reach design product assay	+ full assay span can be achieved with few centrifuges installed—flexible
	+ plant expansion gives lower cost separative work	· plant expansion gives separative work at similar cost
Power	— requires large blocks of firm power	+ uses less power
	— power requirement may limit siting options	
	— power requirement may impose a long lead time on plant construction	
	— waste heat rejection may impose siting restrictions	
Supporting Industrial Base Capability	+ exists now in United States	— a new industry must be established

is pretty well understood, further technological innovation and cost reductions are possible, particularly in building entirely new plants. Among the areas that have been mentioned are better stage designs, replacement of electric with steam turbine drives, power recovery systems, even larger stages, and reductions of plant construction capital costs. Any new U.S. diffusion plant could be built with better technology than the best technology available at the end of the present billion-dollar cascade improvement program.

In the case of our centrifuge technology, the primary need is to demonstrate the performance, reliability, and cost figures that have been projected. The limit to future improvements is not as well known as that for diffusion. The lower power requirement, though offset as a cost element, is of some importance in the energy-short climate of today. An aggressive program to demonstrate centrifuge performance, reliability (ETF), producibility (CPLs), and operability (CTF, DCEF) is under way and will yield the information needed.

We are in the fortunate position of now having two viable candidates, and with time there may be others. Also, with time and advancing technology, the picture may change. At this writing, the two viable candidates for us are diffusion and centrifugation. Diffusion is assured; there are greater risks with centrifugation. But there are options available with each process not offered with the other, and these options provide flexibility to the planner and decision maker. To cite one example, the centrifuge process (assuming success in the demonstration thereof) appears to be the logical choice for providing "small" capacity plants, whereas diffusion may be the logical choice if "large" capacity blocks are desired. It is the substantial economic advantage that each process can offer in certain situations which so strongly recommends careful analysis as the basis for process selection and makes so unwise either making a choice by coin-flipping or making a decision to eliminate one process or the other from further consideration.

A balanced perspective is, unfortunately, not always an integral part of all our debates on diffusion versus centrifuge versus lasers versus process X. For example, one contention heard sometimes is that "diffusion requires too much power," therefore centrifugation is preferred. Part of the perspective needed here is furnished by the unit cost of separative work which fairly accounts for the cost of the power required for each process. Choosing centrifuges does mean only one-tenth as much power is required, but other costs offset these cost avoidances. Further perspective is gained by considering the amount of power generated by the reactors the diffusion plant serves. The power consumed in diffusion enrichment amounts to only three percent of the power generated by the nuclear reactors served by the enrichment plant. By way of comparison, a nuclear power generating plant uses about five percent of its output for on-station requirements. Another overall perspective sometimes not kept quite in balance is that of the "huge" capital costs of enrichment plants, with diffusion sometimes made out incorrectly to require larger capital costs than centrifugation. The cost of both diffusion or centrifuge plants is certainly very large; but as pointed out so nicely by Baranowski in a recent address (ref. 6), the capital investment in enrichment needed to support a 1000-Mw(e) reactor is about $12 million*, compared to $500 to $700 million for the reactor itself. This investment is less on a per-reactor basis than the capital required for the mining and milling investment to supply the uranium feed material ($16 to $33 million per reactor). In our eagerness to make the right process selection and to reap the substantial economic benefits to be gained by doing so, we must be mindful of the relation of these decisions to the other equally or even more significant decisions that must be made in other parts of the nuclear industry.

* He assumed $1500 million for capital cost of an 8.75 million SWU/yr enrichment plant which would service 120 reactors.

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